Engineering Case Library

ECL 88

A Case Study

Designing a Transformer

"I first explored the idea of making a solid-state, three-phase laboratory power supply while I was doing graduate work at Stanford back in 1961," explained Mr. Roy Kaylor, proprietor of Advanced Energy Conversion in Menlo Park, California. "In this age of the transistor, nearly everything electronic has been converted to solid-state circuitry. One exception is the type of power supply that provides balanced three-phase power for laboratory use. I'm presently developing a solid-state power supply that I anticipate will get a lot of use in the testing of gyroscopes, motors, and military and aircraft equipment. The breadboard model of this device is about half finished now and I'll probably have it ready for testing within the next two months."

Prepared by William Clemens under the supervision of Professor Ralph J. Smith, Department of Electrical Engineering, Stanford University with support from the National Science Foundation.

The main reason behind building a breadboard version of a product is to "debug" it - to see how all the parts work together. In this stage of the development process Roy would select the sizes and ratings of the components as well as determine how they would fit into the spaces he had planned for them. During this stage of development, he would be "optimizing" the power supply for performance and weight. The next step would be to optimize the product for cost, i.e. choose the components (resistors, transistors, capacitors, transformers) and the manufacturing processes that would result in the least expensive, most reliable power supply.

One of the circuits Roy was working on serves to induce "trigger" pulses into an adjacent circuit through a transformer. "Small details become very important when you start selecting components," Roy pointed out. "For example, the transformer in my control circuit will probably cost only a couple of dollars, but there are several different types of transformers that will work. The price per unit varies with the quantity ordered. Physical characteristics such as dimensional tolerances can make a big difference in the time, and therefore cost, of assembly of the power supply."

Roy Kaylor and Advanced Energy Conversion

Advanced Energy Conversion, the name Roy gave his small electronics business, develops and markets special purpose power supplies for laboratory and and aerospace applications.

Roy's interest in power supplies arose from his experience as a private pilot. "I started flying in the Stanford Flying Club while I was still an undergraduate," he explained. "I soon realized that good instrumentation was not available at prices private pilots could afford. Most small planes lacked artificial horizons, altitude indicators, directional gyros, and other desirable navigational equipment." Roy was aware that light weight surplus military instruments were available at

relatively low cost, but he knew that they required 400-cycle, 3-phase power, and on small planes only 12-volt d.c. power is available.

During his senior year in college Roy began developing and designing power supplies to fill this need. He designed and sold a line of small power supplies that could be mounted in, or behind, the instrument panels of small airplanes. "The market for this kind of device was fairly small and no large companies had entered the field," Roy said, "so I had the market around here pretty much to myself. I made enough off my small business to send myself through grad school for a master's degree."

While he was a part-time graduate student, Roy worked with some local companies. However, he wasn't enthusiastic about the jobs he held. "One company I worked for," Roy explained, "depended almost entirely on government contracts. I had been working for them only a few months when they lost a big contract they were bidding on. Apparently, they didn't have any other 'irons in the fire' so they laid off about 90% of their engineering staff - including my whole section." Roy worked for two other firms for awhile but found that he wasn't doing the type of work he was interested in, so he decided to devote most of his time to his consulting and manufacturing business. "You usually don't make as much money to start in your own business," he explained, "but the potential rewards are much greater than if you work for another company all your professional life. Aside from that, I find that the work I'm doing now is much more challenging than what I was doing in industry. There is also a lot of personal satisfaction in seeing your own ideas materialize into an actual product that people need and are willing to pay for."

Roy is gradually moving out of the aircraft supply business and is concentrating on his other products: power supplies for laboratory use, frequency changers, special duty three-phase rectifiers, and some miniature inverters* to operate cooling fans for electronic equipment.

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* inverter - an electronic device to change direct current into alternating current.

Development of the Power Supply

Roy began the development of a laboratory power supply as part of his master's project at Stanford back in 1961. "My experience with small, solid-state, 400-cycle, 3-phase aircraft inverters led me to this choice for a project," he recalled. "I became very interested in switching theory, and that led me to an idea for constructing a simple, lightweight power supply. Supplies that served the same function as the one I had in mind were available, but they were very bulky and none of them, to the best of my knowledge, made use of switching theory as I intended to in mine."

The purpose of Roy's power supply was to convert ordinary household power into three-phase, 400-cycle power. His idea was to change the single-phase, 60-cycle * a.c. input into three 400-cycle, single-phase outputs and then combine them into a balanced three-phase supply.

A schematic diagram of Roy's original plan of attack is given in Exhibit I. A controlled oscillator is used to drive a "trigger" that supplies pulses at intervals seconds apart. The pulses, in turn, activate a "ring counter", which is a switching device used to direct an input voltage to one of its six outlet terminals. Referring to Exhibit I, if the voltage is initially ON at terminal a, the first pulse from the trigger will switch the voltage from terminal a, to terminal b. Similarly, succeeding pulses will switch the voltage from terminal b to c, then from c to d, from d to e, from e to f, and finally from terminal f back to terminal a. The output voltage from each of these terminals is channelled into two "OR gate"**. The result is a set of voltage waveforms as shown. By combining the output voltages as indicated, three periodic alternating output voltage waveforms are produced, each made up of positive and negative rectangular pulses (for a comparison between the actual waveform

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* "60-cycle" is slang for a frequency of 60 cyclesper second; the new international unit of frequency is the Hertz where I Hertz (Hz) is equal to I cycle per second.

** "OR" gate" No. I provides an output voltage when there is an input voltage at terminal a "OR" terminal b.

of one of these outputs and the sinusoidal signal it is intended to approximate, see the appendix).

Roy built a working model of his power supply as part of his master's project to demonstrate the validity of the analysis in his thesis. This model worked as predicted, but it wasn't a marketable item in its then crude form. Roy didn't actually start the design of a production model power supply until six years later. "When I built my demonstration model, there didn't appear to be much commercial interest in a power supply of this type," Roy explained. "However, solid-state technology has received a lot of attention recently, so I decided to invest some time and money in an attempt to 'sound out' the current market at one of the large electronics shows on the coast.

"I rented a booth at the Wescon Show* in August, 1967, and displayed a model of what the finished power supply would look like (see Exhibit 2) along with some of the other products I have designed and marketed. I also ran off some 'hand-outs' on the new power supply to distribute at my booth at the show."

Shown in Exhibit 3 are the leaflets Roy used at the show. They give a description of the capabilities, size, weight, and estimated delivered price of the power supply. In estimating the selling price of his power supply, Roy priced all the components needed in each unit, including the case, and multiplied the sum of these individual prices by a factor of 2.5. He had arrived at this factor by comparing the total cost and component prices of the small power supplies he had already sold. "After I had made this estimate (about $500)," explained Roy, "I went around and priced some of the competition. I found supplies with about the same ratings as mine sold for $1400 to $3000 per unit, so I set $895 as my tentative selling price. I couldn't be too sure of the eventual cost of making these instruments, but I thought that this price would be pretty attractive to potential customers and would still leave my some margin in case my original cost estimate was poor."

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* Sponsored by the Western Electronic Suppliers Convention.

Roy reported that at the show he had "about 40 bonafide inquires" on his new power supply, with one aircraft company showing an interest in buying 10-20 of the new instruments when they became available. "To make it worth my while," Roy continued, "I estimated I would have to make a trial production run of between 100 and 1000 units. The interest I found at the show indicated to me that I could reasonably expect to market that many units, so I started the detail design of a production unit."

Design of the Power Supply

Next Roy began building a "breadboard" model of the production version of his power supply. The production version differs from his master's project primarily in the extensive use of integrated circuits to conserve space and weight.

Among the principal components of the improved power supply are three sets of synchronous switches and a switching regulator. The synchronous switches are used to transform a high voltage d.c. into the three 400-cycle, single-phase outputs (They replace the ring counter of Exhibit I). The switching regulator employs an integrated circuit to provide the required constant d.c. voltage.

A schematic diagram of the switching regulator is shown in Exhibit 4. Rectified 115-volt single-phase alternating current provides the 160-volt d.c. power for the regulator. A very small variation in the output voltage is picked up through a potentiometer connected to terminal 6 of the integrated circuit, compared to an internal reference, and converted to a digital signal of variable pulse width. This digital signal is then amplified and fed through a transformer to drive a power switch that provides a change in current to compensate for the voltage variation. This transformer is the one Roy is "optimizing" for performance and cost.

The purpose of this transformer is to "couple" two circuits together while providing voltage isolation between the two. A change in voltage across the primary coil produces a corresponding change in magnetic flux in the ore of the transformer. The change in flux, in turn, causes a change in voltage across the secondary coil of the transformer. This change in voltage causes a current to flow through resistor R_1, allowing the transistor switch to open. This causes a considerably greater current to flow through the output circuit. Because the integrated circuit responds to very small variations in the output voltage, the switching regulator supplies a very uniform output voltage.

In the design of a transformer whose operating requirements are known, there are generally four considerations: resistance power losses in the windings, eddy-current power losses in the core, size (compactness and dimensional tolerances), and cost.

"I need a resistor in series with the transformer secondary anyway," Roy explained, "so resistance losses aren't too important to me. My main considerations in picking the right transformer will be size and cost. I plan to use printed circuits in the production model power supply to save on labor, so my primary concern is to select a transformer with a good 'packaging factor' - a small, compact unit with good dimensional tolerances."

In small transformers, the most common types use ferrite, tape-wound, or laminated cores. An example of each type of core is shown in Exhibit 5. In a ferrite core transformer, the primary and secondary coils are usually wound together on a plastic bobbin which is often enclosed inside two mating core halves. The cores themselves are made of powdered iron oxide which has been pressed into the desired core shape then baked. In tape-wound core transformers, the cores usually are made by rolling strips of grain-oriented magnetic material into tight rectangular

or circular coils. Primary and secondary coils are then wound toroidally on the cores or the cores are cut and coils previously wound on bobbins are placed on them. Laminated cores are made up of stacks of thin sheets (laminations) of ferrous material which are clamped or bolted together. In this type of transformer, the coils are usually wound on bobbins which are then placed over the "legs" of the laminations.

When he began selecting components for his power supply, Roy immediately eliminated tape-wound cores from his list of possible cores. "Tape-wound cores really aren't very satisfactory for use in mass production," Roy pointed out. "The manufacturers usually cannot hold very good dimensional tolerances. Often the cores will not fit in the bobbins and I've found you have to reject about 20% to 30% of every shipment for this and other reasons. To go to printed circuits, I need better tolerances than are available with this type of core. Since tape-wound cores aren't substantially cheaper than other types of cores, I decided to stay clear of them."

The other two types, ferrite and laminated cores, can be manufactured to acceptable dimensional tolerances. Roy's ultimate choice will depend primarily on unit transformer cost.

Choosing a Transformer

Roy's choice of a transformer core will be governed primarily by the number of power supplies he expects to sell with each production run. "I hope to have production runs approaching 1000 units," Roy pointed out, "but that depends on how many advance orders I can solicit. In any event, the production runs will be no smaller than 100 units each so I have some guidelines by which I can choose a set of components for the power supply."

When he had completed the testing of his breadboard design and was satisfied with the performance of the circuitry, Roy began "shopping around" for parts.

Listed below are the data he was given by two electrical supply firms on core laminations and ferrite cores:

Ferroxcube (ferrite cores)

Units Ordered	1-24	25-99	100-499	500-999	1000
core half (each)	1.05	.74	.47	.35	.35
round bobbin	.145	.095	.065	.055	.050
mounting hardware	1.16	.68	.45	.40	.36

E-I-375 Laminations

0.014" thick laminations

0-15 lbs. $4.302 per pound

over 15 lbs. $3.914 per pound weight per stack: 0.1045 (.375" thick)

square bobbin - same cost as for round bobbin used with ferrite core.

Ferrite core transformers are usually made by winding both primary and secondary coils on a bobbin, and securing the bobbin inside two mating ferrite halves. This assembly can either be held together with a nylon screw or with the mounting hardware listed in the tables above. The mounting hardware is not necessary but makes it more convenient to mount the transformer to a circuit board. Roy estimated it would take about 10 minutes for an operator to wind one of the round bobbins and another minute to assemble the transformer (at a cost of about 4 to 5 dollars per hour).

Laminated core transformers require more labor to assemble than ferrite core transformers because the laminations have to be stacked by machine or by hand. Roy said he would probably use the common E-I type laminations if he decided to use laminations at all. Each layer of this type of core is made up of two pieces of iron arranged as shown in Figure 1. The core itself is made up of a stack of

layers equal in height to the width of the center leg or "tongue" of the
The primary and secondary coils of the transformer are wound on a square bobbin which fits over the tongue of the stack of **E-I** laminations. Roy estimated it takes about 12 minutes to wind a square bobbin and about 5 to 10 minutes for a practiced operator to stack and assemble a laminated core transformer.

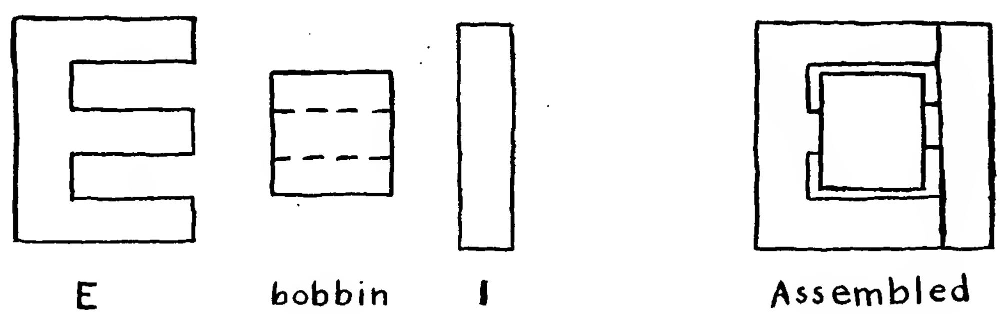


Figure 1

"There are other costs involved in making a transformer besides the cost of materials and assembly," Roy pointed out. "There are also overhead costs including machine depreciation and power, but they don't vary much with the number of units produced. For my transformer, I can get a pretty good idea of the relative costs of using the two different types of cores just by comparing the unit costs of the two types of transformers for my anticipated production run."

Appendix

Any "piecewise continuous" periodic function, f(t), can be represented by an infinite series of sinusoidal functions of the type:

$$f(t)= A_1\sin(\omega t-\theta_1) + A_2\sin(2\omega t-\theta_2)+ \dots +A_n\sin(n\omega t-\theta_n) + \dots$$

or in a more compact form,

$$f(t)=\sum_{n=1}^{\infty} A_n\sin(n\omega t-\theta_n)$$

where A_n and θ_n are constants that are determined by the "shape" of the periodic function, f(t). This is one form of the widely-used Fourier Series. The frequency, ω, of the first or "fundamental" harmonic of the series $[A_1\sin(\omega t-\theta_1)]$ is equal to $2\pi/T$ radians per second where T is the period of the given function, f(t). The frequency of the second harmonic is twice that of the first, and the frequency of the nth harmonic is n times that of the first.

One of the three single-phase outputs of Roy's power supply can be represented as follows for one cycle;

$$f(t) = \begin{cases} 0; & 0 \le t \le \pi/6\omega \\ A; & \pi/6< \le t \le 5\pi/6\omega \\ 0; & 5\pi/6\omega \le t \le 7\pi/6\omega \\ -A; & 7\pi/6\omega \le t \le 11\pi/6\omega \\ 0; & 11\pi/6\omega \le t \le 2\pi/\omega \end{cases} \qquad (1)$$

and the Fourier series representation is

$$f(t)= A\,\frac{2\sqrt{3}}{\pi}\,[\sin(\omega t) - \frac{1}{5}\sin(5\omega t) + \frac{1}{7}\sin(7\omega t) \dots \qquad (2)$$

Plotted in (Figure 2) are equation (1) and the first harmonic from the series in equation (2). Plotted in (Figure 3) is the difference between the two functions in (Figure 2) along with the fifth harmonic of f(t), i.e., the second term in equation (2). By inspection of (Figure 3) it can be

seen that the difference between f(t) and the first harmonic of equation (2) is dominated by the fifth harmonic of f(t).

In his power supply, Roy obtains a sinusoidal function of frequency from a rectangular periodic function, f(t), that contains the desired sinewave at the fundamental frequency, a smaller fifth harmonic, and some still smaller higher harmonics. The power generated in each of the harmonics is proportional to the square of its amplitude and, since all but the fundamental are small, the power represented by unwanted harmonics is very small. Through the use of electrical filters, Roy is able to practically eliminate the effect of the higher harmonics.

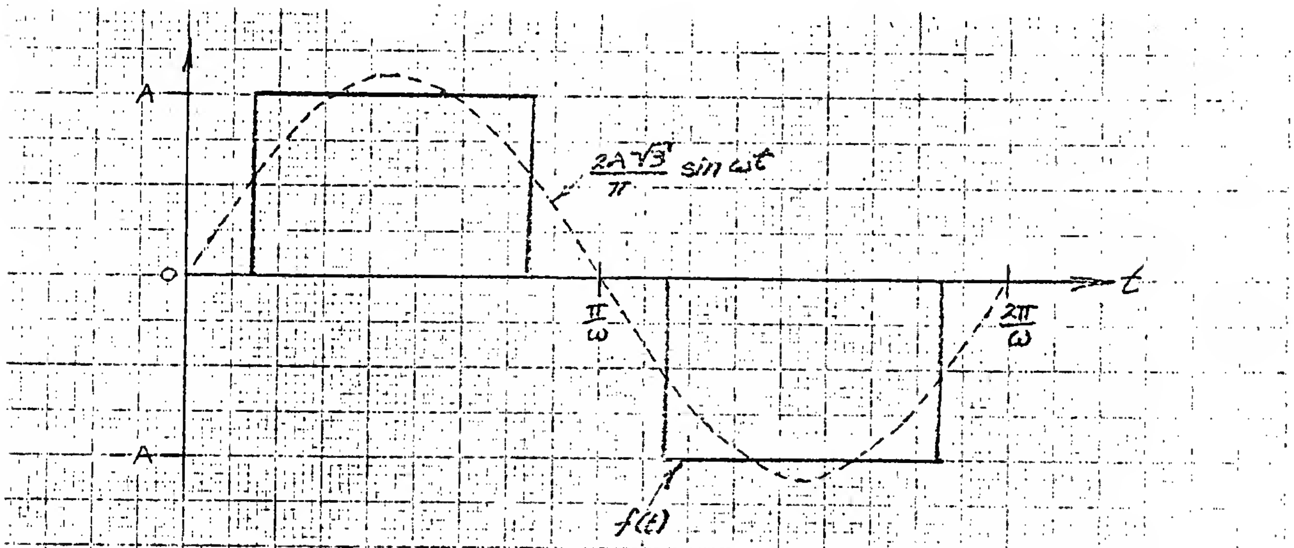


FIGURE 2

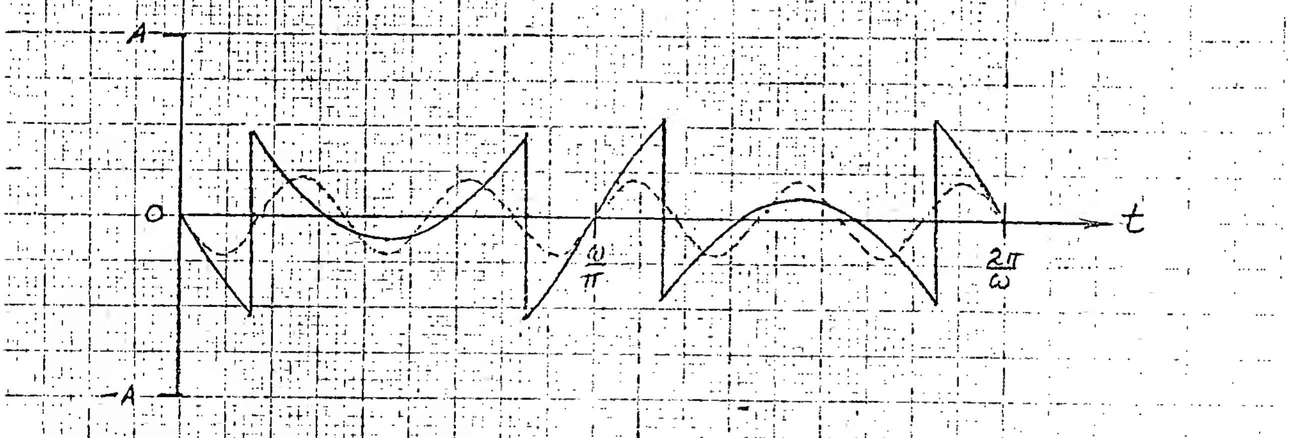
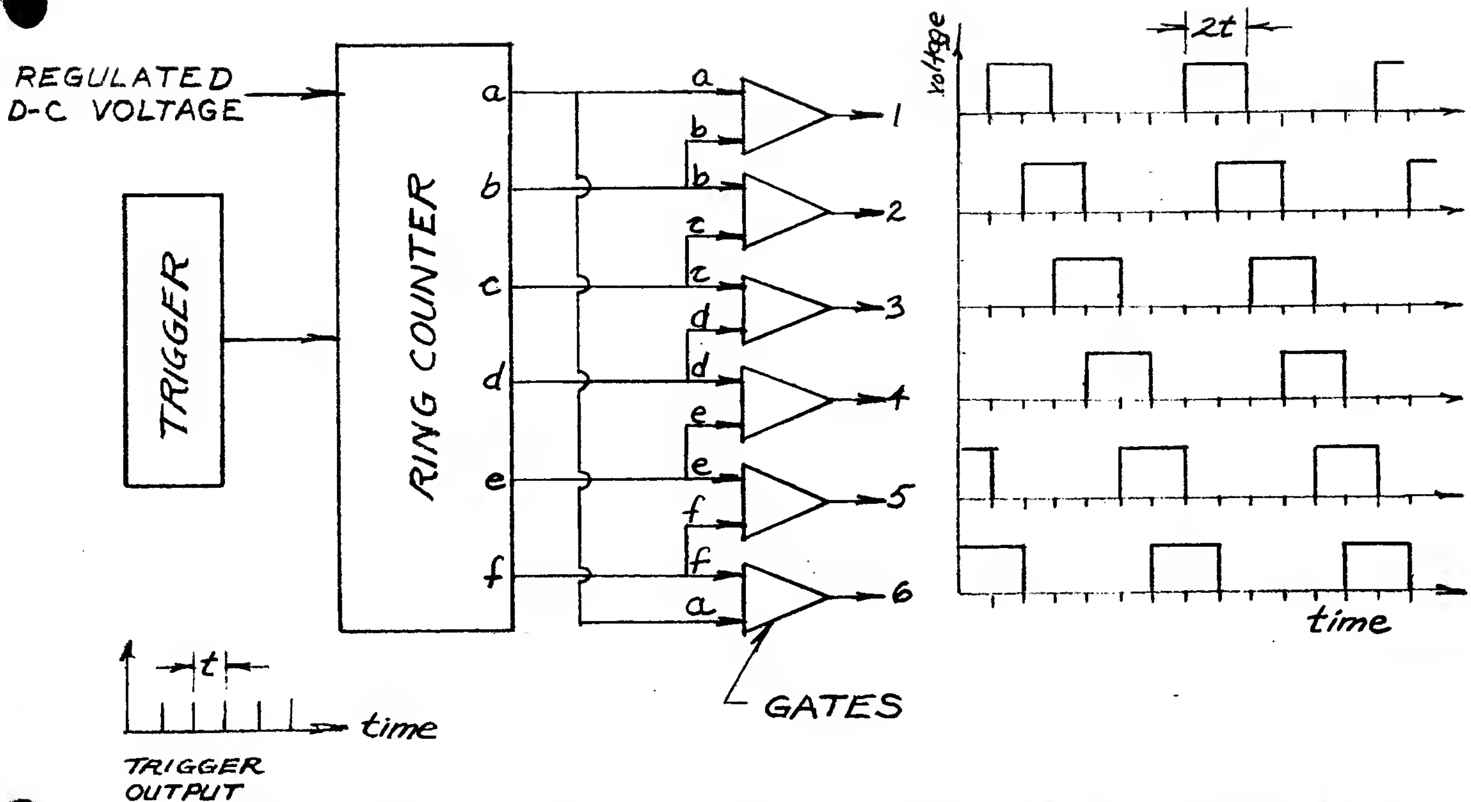
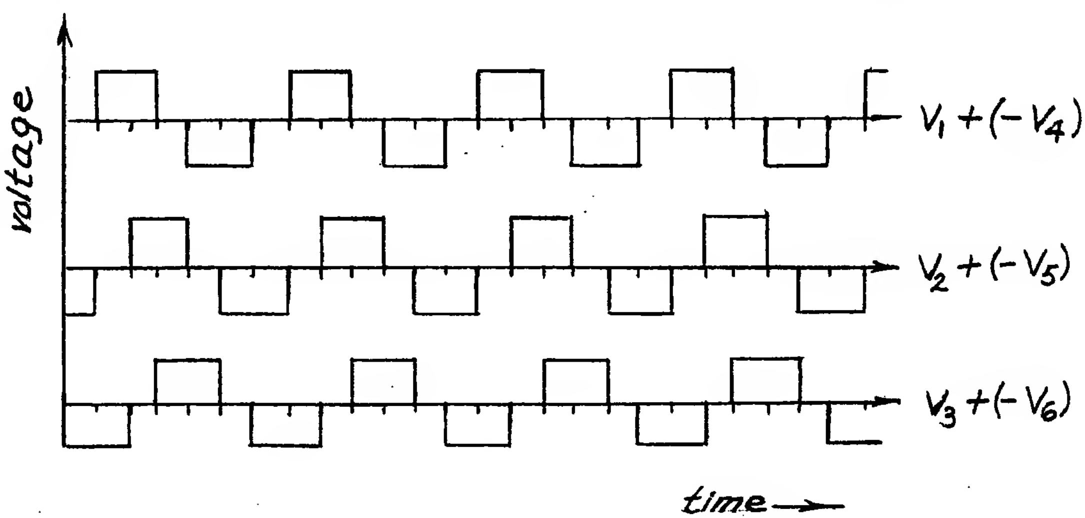


FIGURE 3

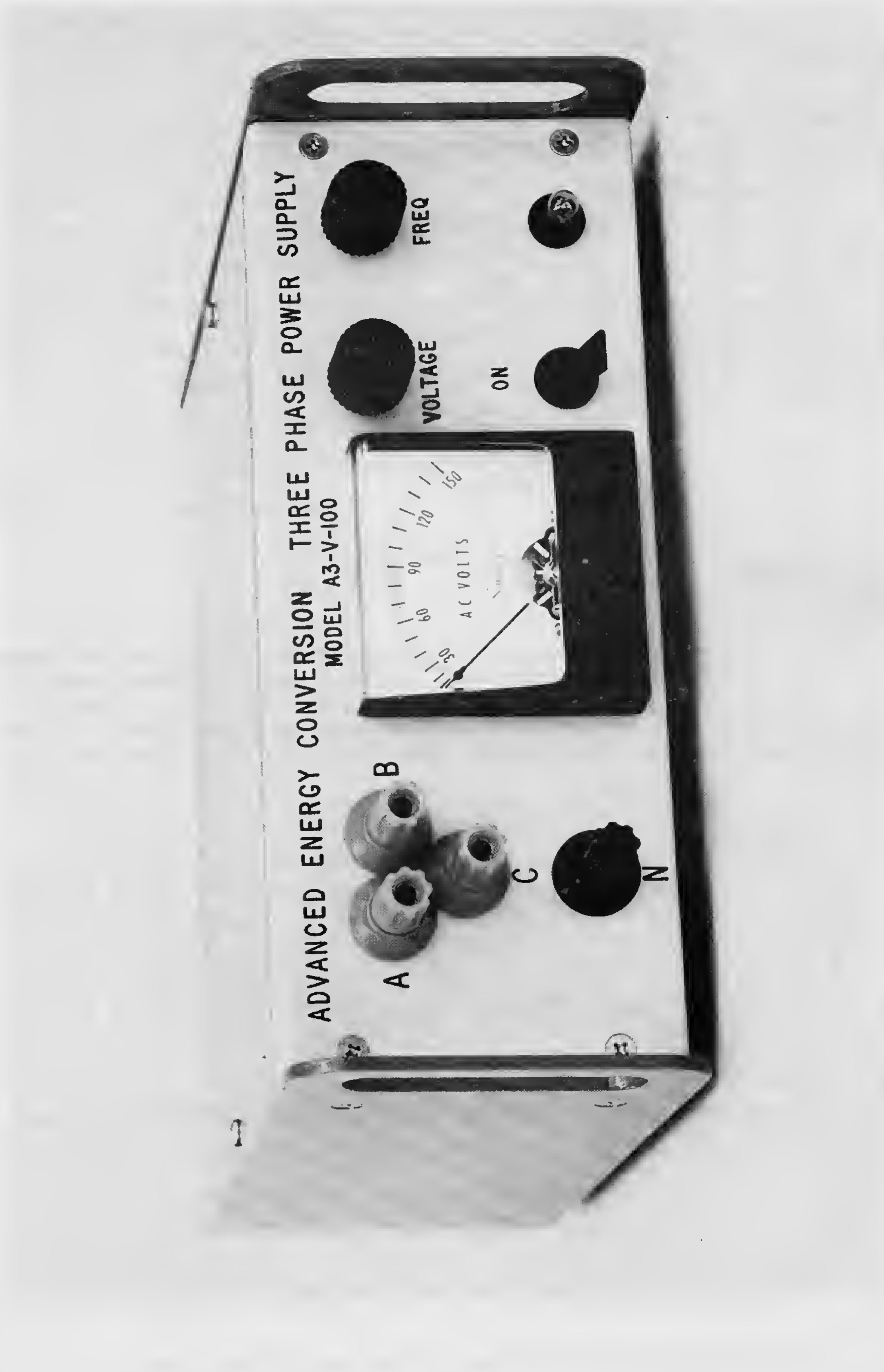
Exhibit 1 ECL 88



TO OBTAIN THREE ALTERNATING OUTPUT VOLTAGES FROM THE WAVEFORMS ABOVE, FIRST INVERT THE VOLTAGE FROM 4 AND SUPERIMPOSE IT ON 1. THEN INVERT THE OUTPUT FROM 5 AND SUPERIMPOSE IT ON 2. FINALLY INVERT THE OUTPUT FROM 6 AND SUPERIMPOSE IT ON 3. THE THREE RESULTING WAVEFORMS ARE ILLUSTRATED BELOW.



Schematic Diagram of Kaylor's Plan for the Power Supply



Model of Finished Power Supply

October 9, 1967

Advanced Energy Conversion's small, lightweight, quiet, electronic frequency changer for laboratory use provides 250 Volt amperes of 400 hertz, three-phase power, useful for testing gyroscopes, motors, military and aircraft electronic equipment.

The remarkable miniature size and low weight of this instrument result from the extensive use of integrated circuits and advanced switching techniques. The all silicon circuitry provides exact three-phase relationships under all conditions. Each phase is short circuit protected and current limited. Overload of any phase removes power to all phases protecting three-phase loads.

The output frequency is crystal controlled to insure high accuracy, 400 hertz power. The user may also vary the output frequency continuously over the range of 400 hertz ± 10%. A special rear panel jack has been provided to allow the reading of the output frequency on a counter.

The advanced techniques employed in this unique instrument make it possible for us to offer to you the low price of $895.00.

Advanced Energy Conversion
1918 Menalto Avenue
Menlo Park, California 94025
(415) 325-9255

SPECIFICATIONS

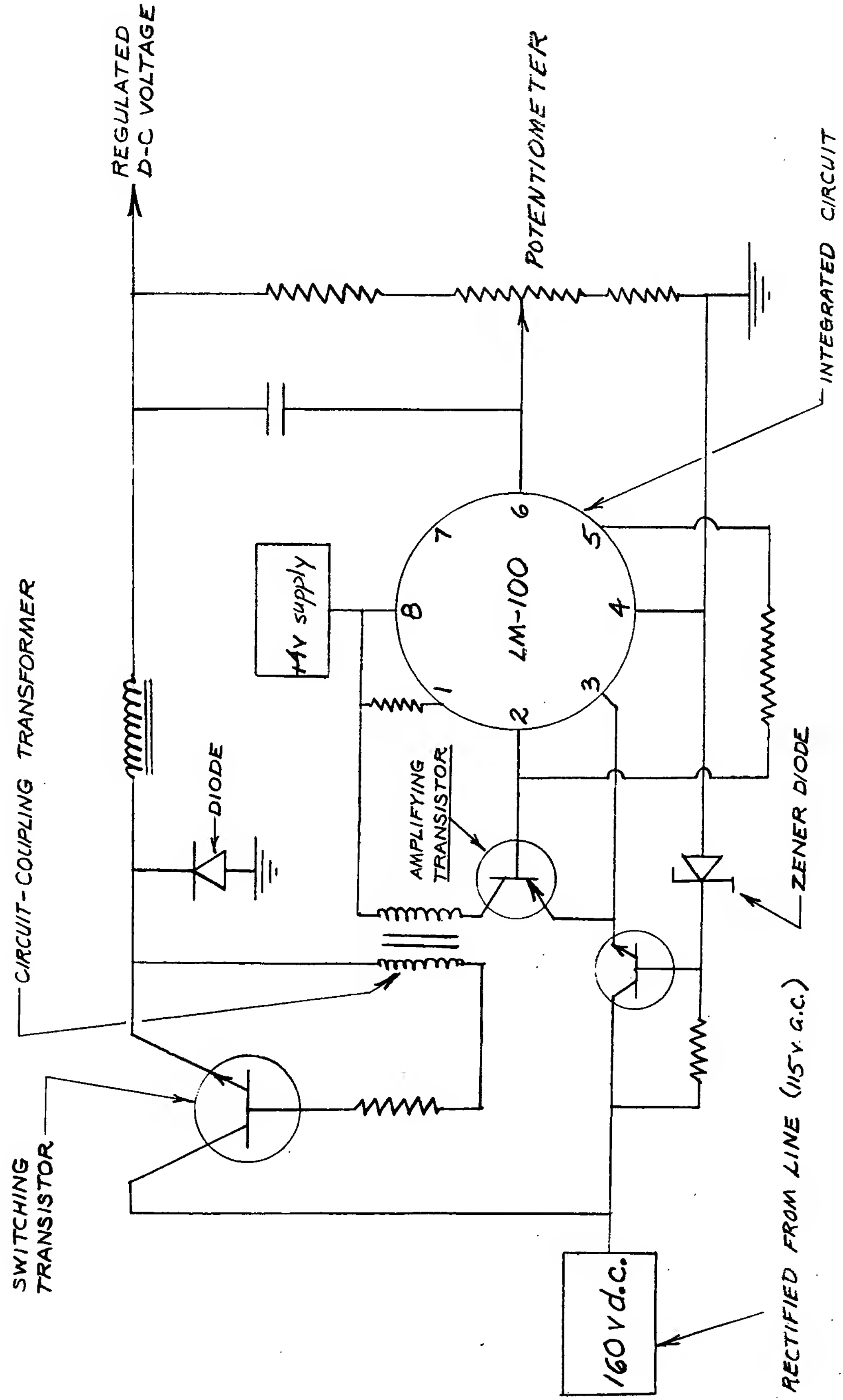
Model	A3-400-250
Input	100-130 VAC, 50-400 Hertz
Frequency	Fixed 400 Hertz ± 0.005% (± .02 Hertz) and variable 400 Hertz ± 10%.
Voltage	Variable, 0-150 VAC. Regulated, ± 5% including no load to full load variation, 0-40° C temperature variation, 100-130 VAC input variation.
Phase	Three-phase. 120 degrees ± 1 degree under all conditions of load and environment.
Power	Total of 250 Volt Amperes maximum continuous at full output voltage. Power available decreases linearly with voltage.
Waveform	Synthesized sinusoidal wave. Less than 10% harmonic power under all conditions of load and environment.
Size Weight	8 1/2" (21.6 cm.) wide, x 3 1/2" (8.9 cm.) high, x 7" (17.8 cm.) deep. Under 15 lbs. (6.8 kg.)
Price	$895.00, fob destination.

Advanced Energy Conversion

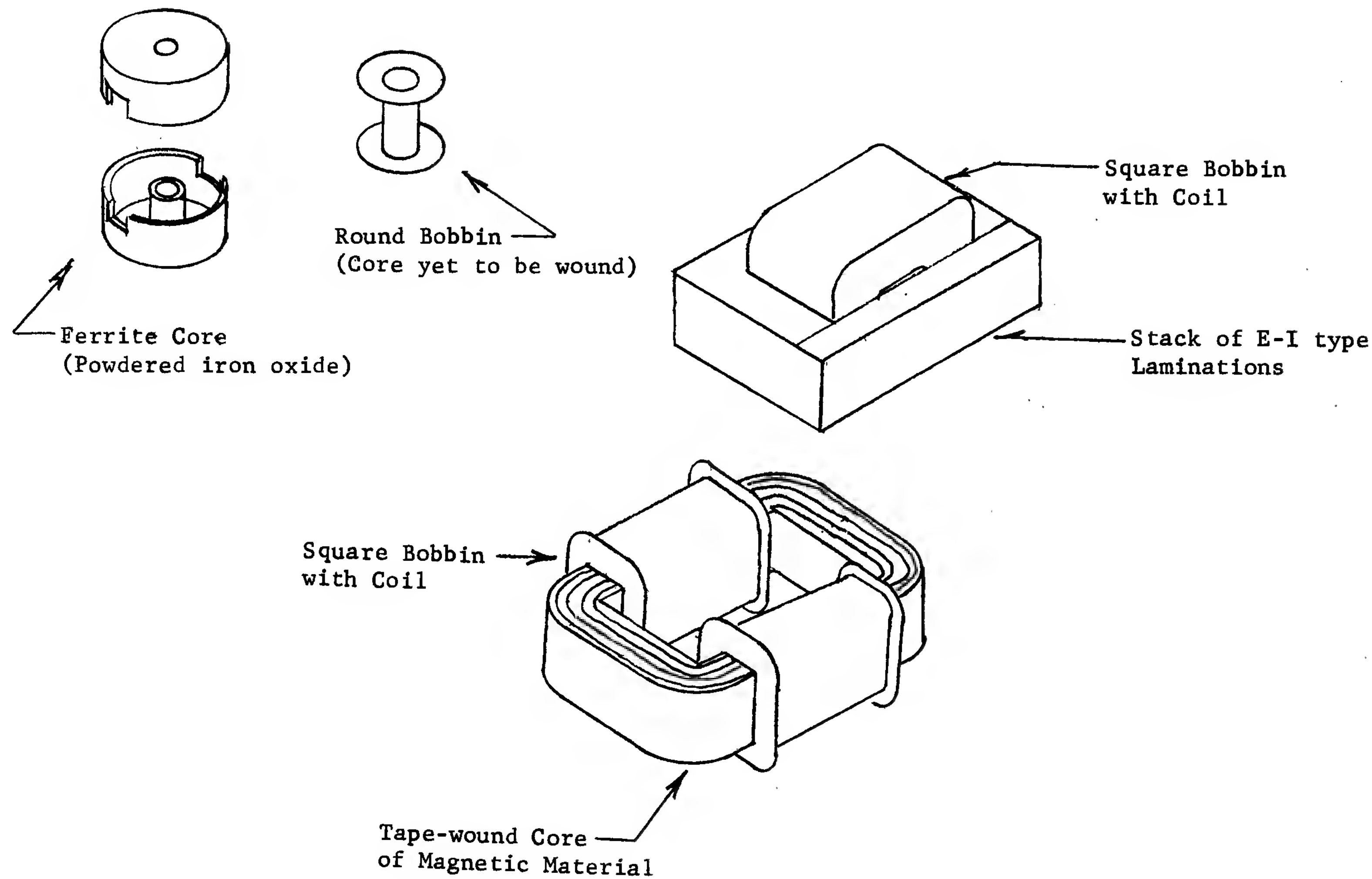
1918 Menalto Avenue

Menlo Park, California 94025

(415) 325-9255



Schematic of Power Supply Voltage Regulator



Examples of Three Common Transformer Cores Now in Use.